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14. ABSTRACT

The Naval Research Laboratory (NRL) Oceanography Division has implemented a 1/25° horizontal-resolution numerical ocean model for the Gulf of Mexico (GOM). The model domain encompasses the entire GOM extending from 18° to 31° North and from77° to 98° West. The physical formulation is based on the Naval Coastal Ocean Model (NCOM) configured with a 40 level -z vertical structure: 19 terrain-following (sigma) levels at the top of the water column, and 21 z (depth) levels at the bottom. The terrain-following levels, reaching from the surface to about 137 meters, allow higher vertical resolutions for resolving mixed layer/shallow waters, while the z-levels are used in the stratified ocean. The ocean bathymetry is constructed from the NRL 2-minute database with the coastline set at a depth of 2 meters. The physical model is one-way coupled to a 13-component ecosystem (biogeochemical) model [Chai et. al., 2002, 2003, 2007] that includes nutrients, two classes of plankton, as well as O and CO2. The current configuration is tailored, but not limited to, real-time (RT) prediction; providing nowcasts (current state of the ocean) and up to 120-hour forecasts for the region. In this configuration, the model receives (initial) boundary information from the operational 1/8° Global NCOM, and it is forced by 3-hourly 1/2° momentum and heat fluxes from the Naval Operational Global Prediction System (NOGAPS). The NCOMGOM model assimilates daily surface/subsurface temperature and salinity generated by the Modular Ocean Data Assimilation System (MODAS), which regresses satellite derived Sea Surface Temperature (SST) and Sea Surface Height (SSH) data to obtain T&S synthetic profiles.

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Bio-Physical Ocean Modeling in the Gulf of Mexico

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Abstract-**The Naval Research Laboratory (NRL) Oceanography Division has implemented a 1/25° horizontal-resolution numerical ocean model for the Gulf of Mexico (GOM). The model domain encompasses the entire GOM extending from 18° to 31° North and from 77° to 98° West. The physical formulation is based on the Naval Coastal Ocean Model (NCOM) configured with a 40 level σ-z vertical structure: 19 terrain-following σ (sigma) levels at the top of the water column, and 21 z (depth) levels at the bottom. The terrain-following levels, reaching from the surface to about 137 meters, allow higher vertical resolutions for resolving mixed layer/shallow waters, while the z-levels are used in the stratified ocean. The ocean bathymetry is constructed from the NRL 2-minute database with the coastline set at a depth of 2 meters. The physical model is one-way coupled to a 13-component ecosystem (biogeochemical) model [Chai et. al., 2002, 2003, 2007] that includes nutrients, two classes of plankton, as well as O and CO2. The current configuration is tailored, but not limited to, real-time (RT) prediction; providing nowcasts (current state of the ocean) and up to 120-hour forecasts for the region. In this configuration, the model receives (initial) boundary information from the operational 1/8° Global NCOM, and it is forced by 3-hourly 1/2° momentum and heat fluxes from the Naval Operational Global Prediction System (NOGAPS). The NCOMGOM model assimilates daily surface/subsurface temperature and salinity generated by the Modular Ocean Data Assimilation System (MODAS), which regresses satellite derived Sea Surface Temperature (SST) and Sea Surface Height (SSH) data to obtain T&S synthetic profiles. The model was initialized on January 1, 2009 from the operational 1/8° Global NCOM physical state and from the World Ocean Atlas 2005 and Carbon Dioxide Information Analysis Center (CDIAC) biogeochemical fields. Results from the real-time NCOMGOM nowcasting/forecasting ocean modeling system are compared and evaluated against in-situ and remotely sensed observations, which include bio-optical products processed by the NRL Ocean Color Section. Google Earth/Ocean is used as a platform for viewing the model results interactively and dynamically in real-time. Initial assessment of the model prediction skill is presented along with future plans for improvements and enhancements. The suitability of the system as a tool for decision management is discussed, outlining processes localized to particular areas such as hypoxia, dead zones, wetland loss and degradation, harmful algal blooms, as well as tropical storms and related issues that affect all coastal regions of the Gulf of Mexico.**

I. MOTIVATION

The Gulf of Mexico (GOM) weather plays a significant role in the coastal areas of Florida, Alabama, Louisiana, Mississippi, Texas, and Mexico, with consequences that extend nationally and globally (e.g. oil/gas, fisheries, transportation, tourism, import/export). Accurate prediction of the oceanic/atmospheric and coastal processes that govern this marginal sea is of outmost importance in the socio-economic health of the region. Nothing has elucidated this more than the unprecedented events unleashed by Hurricane Katrina on August 29, 2005.

Motivated by these facts, the Gulf Of Mexico Modeling System (GOMMS) has been implemented as a comprehensive interdisciplinary tool for oceanography research and for Forecasting and Weather Prediction (FWP). There are currently many tools and numerical models for the GOM and its estuaries, but they have specific realizations and/or are tailored to particular needs. The focus in this effort is in creating an integrative modeling framework to address various scientific, managerial, and community needs. From the oligotrophic "blue waters" of the Yucatan Strait to the highly turbid and eutrophic waters of the Mississippi River plume, the GOM provides a wide range of rich and eclectic conditions and ecological habitats whereby many emerging scientific methodologies can be developed, tested, and ultimately be used in other regions of the world.

Major value added contribution from this effort, beyond that of the operational global NCOM, is the coupling of optical and biogeochemical models to the physical Ocean General Circulation Models (OGCMs). The scientific and applied objectives of this interdisciplinary effort will coherently address many of the processes and applications that impact the region: prediction of physical and optical conditions (e.g. turbidity), monitoring and preservation of flora, coral reefs and habitat (e.g. water quality), distribution and migration of ecological processes (e.g. fishery prediction and larval fish recruitment, hypoxia, productivity). Similarly, bio-optical and physical model forecasting is linked to naval requirements such as diving operations, underwater laser performance, mine countermeasures, and expeditionary warfare. Optical responses are clearly characterized in satellite ocean color and provide the linkage to biological processes. Additionally, bio-optical modeling addresses the characterization of sound scattering layers, underwater acoustic propagation, ambient noise, and support for sonar testing. Thus, coupling of physical, optical, and biological models into an integrative system coherently supports scientific objectives, naval requirements, and the needs of coastal managers who make decisions based on the "ocean bio-physical weather". Monitoring and forecasting of the ocean conditions directly supports the decision making capability used in operations and the effective planning in coastal zones.

Although multiple satellite remotely-sensed and in-situ ship, glider and mooring based observations of bio-optical properties are ubiquitous, they are still lacking the spatial and/or temporal density necessary to handle all regional processes. Furthermore,

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observations mostly cover surface or near-surface areas, so numerical models complement the observational data to create a fully comprehensive picture of the ocean environment. In mutual benefit, the numerical solution gains skill from the assimilation of observational data which are also used for the evaluation and validation of the model results.

The GOMMS goal is to optimally leverage the latest available resources and models to set forth a state-of-the-art system; with the notion that as resources become available and better techniques are developed, it will be continually improved to provide the best possible tool for research and FWP in the region.

II. THE GULF OF MEXICO MODELING SYSTEM

The foundation of the system is the integration of a vast array of components, data, and models that have been developed over the years at the Naval Research Laboratory; without these, the GOMMS would not be possible. The following section introduces the fundamentals of the NCOM model and describes the components that comprise the system; all summarized diagrammatically in Fig. 1. There are many configuration/parameterization options for each component, but the specific details are beyond the scope of this paper. In the context of the GOMMS configuration, a synopsis of each system component is mentioned here with the intent of providing overall background information. The reader is referred to the literature for detailed information on each component.

The Naval Research Laboratory has developed several atmospheric and oceanic numerical models. One of these is the Navy Coastal Ocean Model (NCOM) developed by Martin [1] as a successor to the Sigma/Z Model [2] which in turn was based on the Princeton Ocean Model (POM) [3,4]. Like POM, NCOM is based on the hydrostatic primitive equations, but NCOM implements a free surface computed by an implicit scheme which is significantly simpler than the split-explicit scheme used in POM. Furthermore, NCOM implements a hybrid σ-z vertical structure whereby terrain-following layers are used in shallow waters and z-levels are used in the deep ocean. This configuration optimally allows higher vertical resolutions for resolving processes in the upper ocean and subsurface mixed layer, while the z-levels are used in the more homogeneous stratified ocean. NCOM has been running globally as an operational prediction system for over a decade and has successfully served numerous regional modeling efforts, including the implementation of a near-real-time bio-physical model for the California Current System [5]. Thus, the suitability of NCOM as the foundation for the GOMMS became apparent.

The NCOM Gulf of Mexico (NCOMGOM) model is implemented on a Mercator grid at 1/25° (equatorial) horizontal resolution, and a 40-level σ-z hybrid vertical structure (same as 1/8° Global NCOM). Computational resources at the Navy DOD Supercomputing Resource Center (DSRC) have afforded higher horizontal –eddy resolving, and vertical –mixed layer resolving, resolutions, allowing this model to not only provide general circulation and oceanic state at interannual time scales, but also to resolve higher-order mesoscale and coastal dynamics critical to biogeochemical processes. The model incorporates a realistic bathymetry derived from the NRL 2-minute database with the coastline set at a depth of 2 meters, which, complemented by the high horizontal resolution, is capable of resolving shallow estuaries. The domain, illustrated in Fig. 2, extends from 18° to 31° North, and from 77° to 98° West. It covers the entire Gulf, reaching farther east (and south) to encompass the entire state of Florida and to provide a smooth boundary transition.

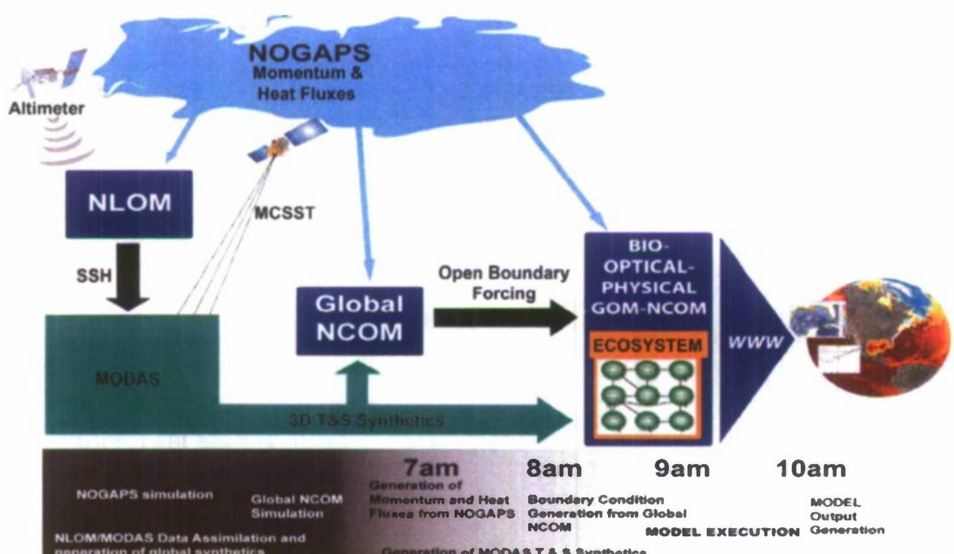

Fig. 1. Component diagram of the real-time Gulf of Mexico Modeling System describing system flow and integration. The timeline at the bottom of the figure represents the daily time at which input/output processing and model execution occur, starting with global prediction systems that run overnight and ending with the generation of the GOMMS model output and Web Portal update at around 10:30am CT.

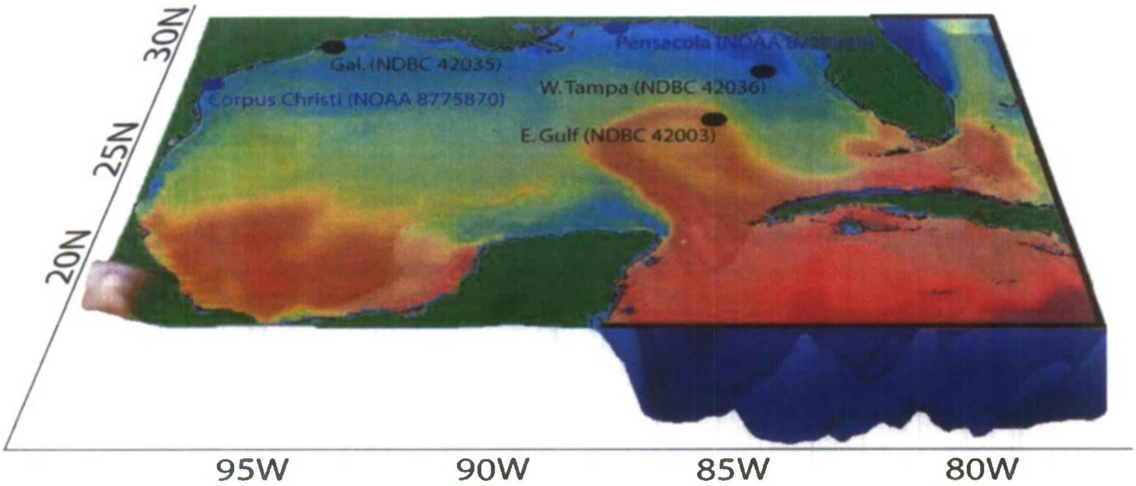

Fig. 2. The GOMMS domain, extending from 18° to 31° North and from 77° to 98° West, illustrates the open boundaries (bold black lines on south, east, and north-east of domain), and the NDBC buoys (black dots) and NOAA tide-gauge stations (blue dots) used for the evaluation of the model SST and SSH; respectively. The color surface field, semi-transparent to reveal the underlying bathymetry, represents the model SST for May 20, 2009.

In the current GOMMS context, NCOM is configured with Smagorinsky [6] horizontal mixing, and Mellor-Yamada Level 2.5 [7] turbulence closure scheme for vertical mixing. Density computation follows Mellor's [8] adaptation of the United Nations Educational Scientific and Cultural Organization (UNESCO) equation of state. Barotropic boundary conditions (surface elevation and normal velocity) use the Flather [9] radiation condition, and baroclinic information is exchanged via vertical structure distributions of temperature, salinity, and velocity fields; namely, tangential velocities use a zero-gradient condition, and normal velocities and tracers (including biology) use an advective scheme. Other formulations are being evaluated to further improve the model skill. River forcing is turned off for all but the Mississippi River and Evaporation-Precipitation (E-P) is not configured at this time. It is expected that salinity prediction will improve once E-P is implemented and all rivers are included.

The GOM ocean model physical state is initialized with and nested within the 1/8° Operational Global NCOM ocean prediction system [10,11,12]. Global NCOM is a Global Data Assimilation Experiment (GODAE) product used by researchers and forecasters around the world, and thus constitutes one of the primary global ocean prediction systems and a major provider of initial and boundary forcing for nested regional and coastal models. Down-scale nesting is not only essential for including oceanic signals, potentially generated far away, vital in modulating the general circulation of a region, but it is also necessary to resolve higher-order scales (in time and space) and localized processes (e.g. biogeochemistry) whose parameterization often requires explicit locale adjustments. The Global NCOM physical fields used for initialization and remote forcing in the GOMMS are Sea Surface Height (SSH), temperature, salinity, and ocean current velocity fields (Table 1). There is a trade-off between boundary updating frequency vs. global model feasibility to output data at higher rates, and as a result, regional/coastal models whose internal time-step is measured in the order of seconds inherently suffer from inaccuracies due to lower frequency boundary updating. For the initial configuration of the GOMMS, the boundaries are updated daily, but to minimize boundary forcing inaccuracies, and taking advantage of Global NCOM 3-hourly output, this configuration will be changed to higher frequencies once the results are fully assessed.

The physical model is one-way coupled to either a 9-component or a 13-component ecosystem model [13,14,15,16]. The 9-component model includes three nutrients (silicate, nitrate and ammonia), two phytoplankton groups (diatoms and small-phytoplankton), two groups of zooplankton grazers (micro and meso), and two detrital pools (silica and nitrogen). Phosphate, oxygen, alkalinity and carbon-dioxide are added in the 13-component model. Initial and boundary values for the ecosystem model are constructed from NOAA's World Ocean Atlas (WOA) [17,18] data and from the Oak Ridge National Laboratory (ORNL) Carbon Dioxide Information Analysis Center (CDIAC: http://cdiac.ornl.gov). Namely the fields: Silicate (SIO), Nitrate (NO_3), Phosphate (PO_4), and Oxygen (O) are constructed from the WOA-2005 monthly climatology [19,20], while Alkalinity (A_T) and Carbon Dioxide (CO_2) are constructed from the time-invariant CDIAC climate data. All other ecosystem constituents are initialized from analytical/literature based values as listed in Table 1.

The ocean model is forced with momentum and heat fluxes from Fleet Numerical Meteorology and Oceanography Center (FNMOC) 3-hourly 0.5° Navy Operational Global Atmospheric Prediction System (NOGAPS) [21,22]. The atmospheric surface forcing fields used are: shortwave radiation, longwave radiation, latent and sensible heat fluxes, and zonal and meridional surface wind stresses (Table 1). The atmospheric forcing forecast fields extend out to 120 hours facilitating forecasting up to 5 days, though climatologically adjusted persistence is used after 3 days because global NCOM only forecasts up to 72 hours.

Table 1. Fields used in initialization of surface and open boundary forcing in the GOOMS ocean model. The sources specify the data provider with the time frequency of each field in parenthesis. All fields are two-(SSH) or three-dimensional and time-varying except those indicated as constants or time-invariant.

Ocean Fields	Source/Value
SSH	Global NCOM (24-hr)
Temperature, Salinity	Global NCOM (24-hr)
Ocean Current Velocity U_x,V_y	Global NCOM (24-hr)
Nitrate (NO3)	WOA 2005 (monthly climatology)
Silicate (SO3)	WOA 2005 (monthly climatology)
Phosphate (PO4)	WOA 2005 (monthly climatology)
Oxygen (O)	WOA 2005 (monthly climatology)
Carbon Dioxide (CO2)	CDIAC (time-invariant)
Alkalinity (A_T)	CDIAC (time-invariant)
Phytoplankton, Diatoms	0.1 (constant)
Ammonium	0.0 (constant)
Detritus, Detritus Silicate	0.0 (constant)
Meso Zooplankton, Micro Zooplankton	0.01 (constant)
Atmospheric Fields	
Surface Wind Stress (τ_x,τ_y)	NOGAPS (3-hr)
Shortwave and Longwave Radiation	NOGAPS (3-hr)
Latent and Sensible Heat Flux	NOGAPS (3-hr)

The ocean model indirectly assimilates satellite derived SSH and SST via the Modular Ocean Data Assimilation System (MODAS) [23, 24]. MODAS uses SSH from the 1/32° (1/16° until March 2008) Navy Layer Ocean Model (NLOM) [25,26,27] to take advantage of the improved resolution and dynamics of the NLOM model over that of the statistical based MODAS. NLOM assimilates altimeter-derived SSH using optimal interpolation and an incremental updating scheme. Multi-Channel SST (MCSST) derived from the Advanced Very High Resolution Radiometer (AVHRR) is ingested by MODAS along with NLOM SSH to constructs temperature and salinity 3D synthetics by regressing SST and SSH towards climatology whose covariance matrices were constructed from historical observations. Salinity is computed via climatologically-based temperature-salinity relationships. The 3D temperature and salinity synthetics (output from MODAS) are then used to relax (constrain) the model to the data using a slow incremental adjustment technique and a 3D time-scale weighting function representing the relative confidence between model and data. For the GOMMS, this function was constructed to account for NLOM SSH not extending over regions shallower than 200 meters, and to take into consideration the inherent near-land inaccuracies of satellite measurements. Specifically, a continuous function of stronger relaxation (shorter time scales) is imposed at the boundary zones and deeper ocean; smoothly tapers off (longer time scales) in shallower areas, and has minimal or no relaxation scales in the near-land coastal zone. This process allows confidence based adjustments to be made and minimizes dynamical disruption.

The model is configured to run once daily at the DSRC on an IBM SP6 computer using 64 processor. The model execution, including pre/post processing, takes about 42 minutes to run a 7-day simulation consisting of 2 hindcasts, 1 nowcast, and 5 forecasts. The model outputs all prognostic variables (see Table 1: Ocean Fields) at 6-hourly frequency. Higher frequency output as well as other prognostic and diagnostic variables, including inherent and apparent optical properties, are available as needed.

III. EVALUATION

Several developmental experiments were run to test the robustness, cost, and performance of the model, including the optimization of the time-step and fine-tuning of the parallelization and scalability. The first production simulation was conducted in July 2009. This simulation was initialized on Jan 01, 2009 and run into the beginning of July 2009. At the time of this paper writing, the evaluation of the results is preliminary, but initial examination indicates that the model is correctly representing the general features of the region. Using higher spatial resolution should not effectively improve the overall physical skill of the model since the atmospheric forcing and data assimilation products used are the same as in Global NCOM, but noticeable differences over Global NCOM, largely accounted for localized parameterization and coastline affinity, have been identified. Future analysis will quantify the improvements that the regional model has over global NCOM.

The major added value of the GOM Ocean Model over that of Global NCOM is the addition of the optical and ecosystem models which are validated against ocean-color observations, namely Chlorophyll from satellite. Fig. 3 shows a qualitative comparison of the GOMMS model computed chlorophyll (diatoms + small-phytoplankton) field vs. MODAS-AQUA observations.

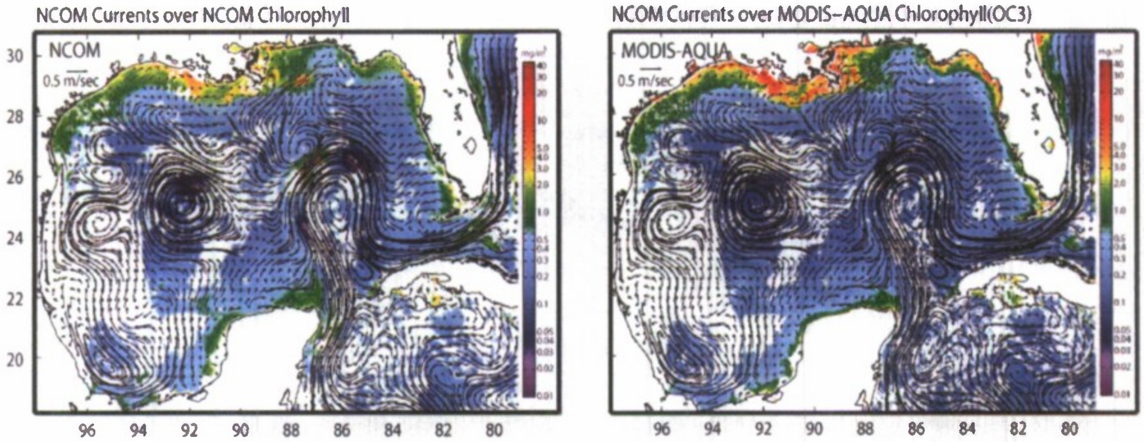

Fig. 3. An 8-day composite (May 25-June 1, 2009) of the Gulf of Mexico region is used as a general qualitative comparison of the model computed chlorophyll (left) to the imagery derived from satellite (MODAS-AQUA) via the OC3 algorithm (right). In order to provide a better visual comparison, the model data was interpolated to the satellite grid and cloud-masked, and the model currents were overlaid on both plots. Although finer coastal features and intensity have not been accurately represented, the general mesoscale structure of the bio-mass is well captured.

The qualitative comparison in Fig. 3 provides an important quality control step to assure that the GOMMS results are representative of expectations. The Chlorophyll comparison to satellite (--an independent data source not assimilated into the system) demonstrates model skill and constitutes an important milestone in the initial evaluation process.

For a more quantitative assessment of the results, the model is validated against independent (not assimilated into the model) surface observations from NOAA's National Oceanographic Data Center (NODC) and National Data Buoy Center (NDBC). Two coastal and one open ocean buoys were selected for the SST comparison, and two tide-gauge stations for the SSH comparison. The buoy locations (black dots) and the tide-gauge stations (blue dots) are depicted in Fig. 2. Model data was skipped when the observations were missing and a 3-day filter was applied to both data sets before plotting and computing the statistics. Fig. 4 shows time-series of modeled SST vs. buoy observations, and model SSH vs. tide-gauge observations whose data was de-tided and corrected for atmospheric pressure. Each panel represents a model-data comparison at each location with the statistical metrics represented by the correlation (r) and the dimensionless skill score (ss) which demonstrate exceptional model skill.

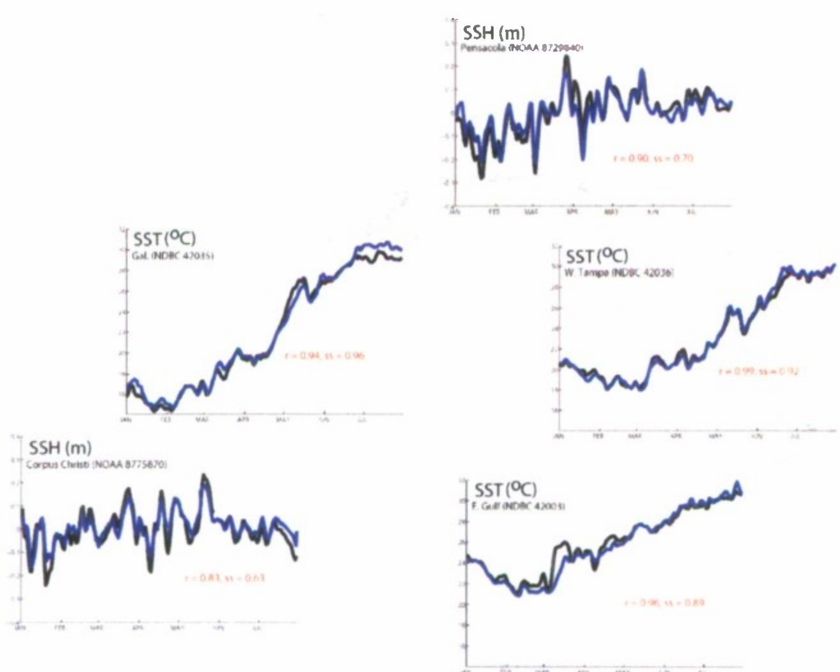

Fig. 4. The correlation (r) and dimensionless skill score (ss) provide a quantitative metric for the performance of the system. Model (blue) SSH anomaly and model SST are evaluated against observations (black) in different areas around the Gulf. Tide-gauge observations have been de-tided and pressure corrected.

IV. SUMMARY AND PLANS

A real-time Gulf of Mexico Modeling System capable of forecasting biological, optical, and physical properties up to 120 hours has been developed. This new capability advances community efforts in the Gulf of Mexico by coupling the Navy's state of the art physical model (NCOM) with a 9 and a 13-component ecological model providing coastal managers and researchers advanced knowledge of bio-physical processes in both the coastal zone and the open ocean. This capability will help predict the influence that large mesoscale processes, such as the Loop Current and the Warm Core rings, have on localized coastal environments, estuaries, and embayment areas like Tampa, Mobile, and Houston. "Bio-Optical-Physical Ocean Weather Forecasting" is a new capability and falls behind present capabilities of Meteorological Weather Forecasting. However, the GOMMS framework augments "OCEAN" weather prediction and brings it to the coastal community by providing real-time access via web portals and earth browsers like Google Earth.

GOMMS is fully modularized whereas all the system components are coupled in a modular "swappable" fashion, with the vision of having a system where other models and tools can be incorporated without major redevelopment. The system is already capable of using initial and boundary forcing from any global ocean model (e.g. HYCOM –HYbrid Coordinate Ocean Model) as well as atmospheric forcing from any atmospheric model (e.g. COAMPS –Coupled Ocean/Atmosphere Mesoscale Prediction System [28]) or observational product (e.g. SeaWinds). Similarly, more sophisticated data assimilation systems, capable of assimilating biogeochemical and optical data, can be incorporated (e.g. NCODA --Navy Coupled Ocean Data Assimilation [29]).

This initial implementation presents an interdisciplinary Ocean Modeling Framework for the Gulf of Mexico complemented with a set of preliminary simulations to demonstrate skill and feasibility. The results presented here show evidence of a successful system implementation. The validation metrics, though not exhaustive, are of reasonable accuracy and provide the motivation to continue the development and enhancement of the system. As the model development progresses, relocatable finer-resolution (sub-kilometer) nests forced by high-resolution COAMPS flluxes will be implemented as 2-way air/sea coupled systems within the GOMMS.

An interactive web portal (http://www7320.nrlssc.navy.mil/gomms) is being constructed as the central point for all activities relating to GOMMS. The site will house the model results in near-real-time, including up to 120 hour of forecasts. As research efforts progress, a comprehensive archive of observational, modeled data, and scientific studies will be available to collaborators, researchers, and government agencies.

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